Plasma source modeling accounting non-LTE radiation transport and level kinetics in-line with gasdynamics

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Introduction

Simulating the emitting plasma requires the usage a self-consistent model that includes gasdynamic equations, radiation transport equation, equation of state, laser energy absorption equation and level kinetics. And of course, it is needed to have radiative properties of the plasma. In general statement it is a complex model. Various simplifications are often used. And one of these is using of prepared tables of radiative properties (absorption coefficients and emissivities). This simplification gives a good gain in calculation time, because in this case it is not needed to solve a big system of level kinetics during RHD calculation, but the accuracy is unknown. In this work we try to compare a few methods of accounting level kinetics and radiation transport with 1D-gasdynamics applied to EUV source problem.

Task statement

- Laser produced plasma based on tin or lithium is considered as a source for EUV-lithography.
- Solution of this problem requires a sufficient accuracy, since we are considering a narrow spectral range (13.5 nm ± 1%).
- Comparison of steady-state approaches with an 'exact' solution of non-stationary level kinetics in a self-consistent calculation with radiation gasdynamics is presented.
- The goal of the work is to determine the effects which are lost when using steady-state tables.

All presented results are obtained using SND_RUSAM code with steady-state and in-line modifications. This code based on self-consistent model of 1D-gasdynamics, radiation transport and level kinetics.

The system of detailed level kinetics

$$\frac{dx_{ks}}{dt} = -x_{ks}\left(\sum_{s'} R_{ks\to k-1,s'} + \sum_{s'} I_{ks\to k+1,s'} + \sum_{s'} T_{ks\to k,s'}\right) + \sum_{s'} x_{k+1,s'} R_{k+1,s'\to k,s} + \sum_{s'} x_{k-1,s'} I_{k-1,s'\to ks} + \sum_{s'} x_{k,s'} T_{ks'\to k,s};$$

Recombination

$$R_{ks\to k-1,s'} = \alpha^{ir} + \alpha^{phr} + \alpha^{dc};$$

Ionization

$$I_{ks\to k+1,s'} = \alpha^{ii} + \alpha^{phi} + \alpha^{ai};$$

Bound-bound transitions: radiative and collisional

$$T_{ks\to ks'} = \alpha^{ex} + \alpha^{abs},\quad T_{ks'\to ks} = \alpha^{dex} + \alpha^{em}.$$

The number of ion states which should be considered for elements with high *Z* can be huge. For example, for tin the number of kinetic equations is about of 100 000. It is necessary to solve this set in each space cell and for each moment of time. It requires enormous computing power even for a 1D gasdynamics. Therefore, it is necessary to use approximations that allow to reduce computing time significantly.

Steady-state approaches:

The system of level kinetics equations is solved in the stationary approximation with a fixed radiation field. Then, using obtained ion states concentration, the tables of absorption coefficients and emissivities are prepared. These tables are used in RHD calculations.

Variants of the radiation field:

1) **Planckian** (LTE or SAHA approximation);
2) **0** (Transparent plasma);
3) **Planckian in band** (Non-transparent in band)

Realized in code **SND_RUSAM TABLE.**

All methods are very fast.

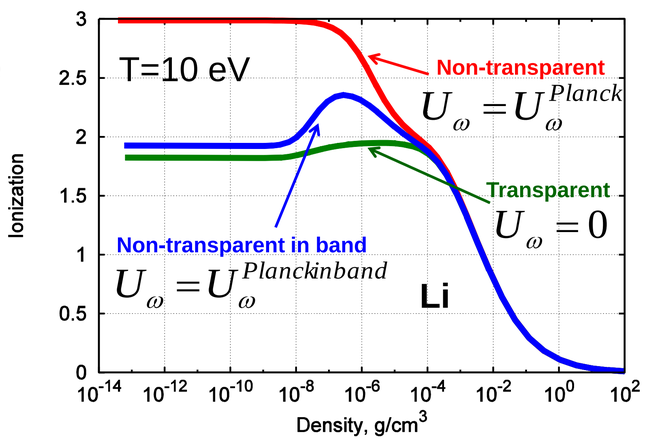
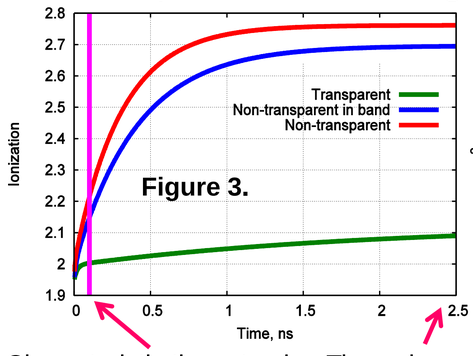


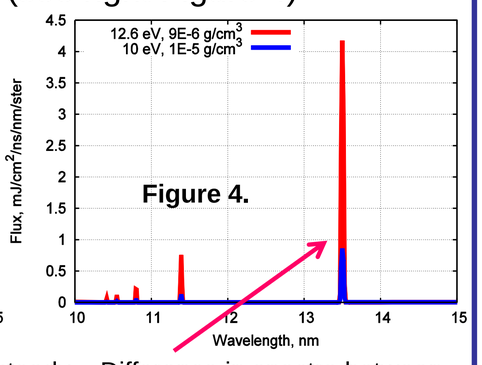
Figure 1. Isotherms of ionization for lithium, obtained in steady-state approximation with Planckian, Planckian in band and without radiation field

Figure 1 shows that at densities less than 1e-4 g/cc there is a substantial difference between LTE case and other cases. This difference in ionization of course leads to difference in radiation spectra. It is very sensitive for EUV source problem where narrow spectral band is considered.

Non-stationary approach:

Let us consider non-stationary solution of the system of level kinetics. At Figure 3 is shown time dependency of ionization for Li during the transition from plasma state with T=10 eV and Rho=1e-5 g/cc to a state with T=12.5 eV and Rho=9e-6 g/cc for 3 considered functions of radiation field. To reach a value of ionization corresponding to the steady state, it takes a long time (a few ns in this case), but in RHD calculations temperature and density can change faster (~0.1 ns). And using steady-state tables, code will start from wrong initial data in the next time step. Errors will accumulated and radiation spectra will be wrong (see right Figure 4).





Characteristic time step in RHD calculation (~0.1 ns)

Time when steady-state ionization is reached

Difference in spectra between initial state and final state is essential

In-line method: In this approach during the radiation gasdynamic calculation at each moment of time and in every space cell the set of non-stationary level kinetics equations is solved. Realized in the code **SND_RUSAM IN-LINE.** The method is very expensive.

SND_RUSAM in-line simulation results

Calculation with the code SND_RUSAM shows that the usage of in-line technique (violet curves) and steady-state methods (other curves) leads to similar distributions of plasma temperature and density. However, the ionization stage is significantly different (see Figure 4). Elementary collisional and radiative processes has characteristic finite times. The Figure 4 clearly shows the effect of "frozen ionization" associated with the fact that at low densities, the time of relaxation is much higher than the characteristic time of the problem, and plasma does not have time to recombine.

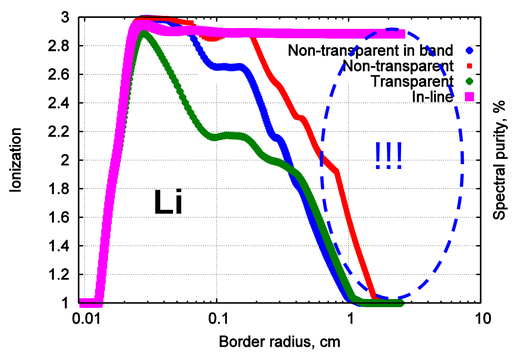


Figure 4. Evolution of ionization for lithium target

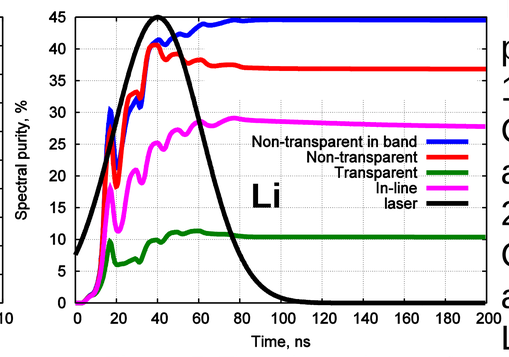


Figure 5. Time dependency of integral spectral purity for lithium

Two test calculations are presented:

1. Sn droplet target(size 100 um); CO2-laser with PD=2e11 W/cm^2 and duration 30 ns.
2. Li droplet target(size 100 um); CO2-laser with PD=5e10 W/cm^2 and duration 30 ns.

Laser model with 100% absorption.

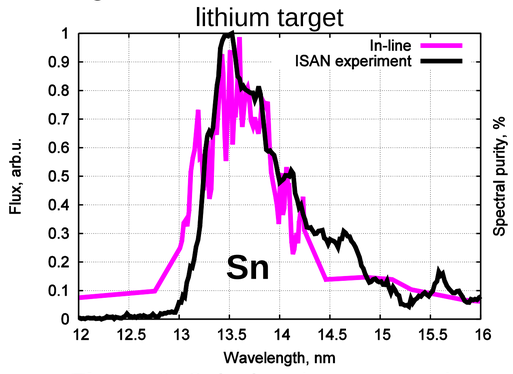


Figure 6. Calculated spectra and ISAN experimental spectra for tin

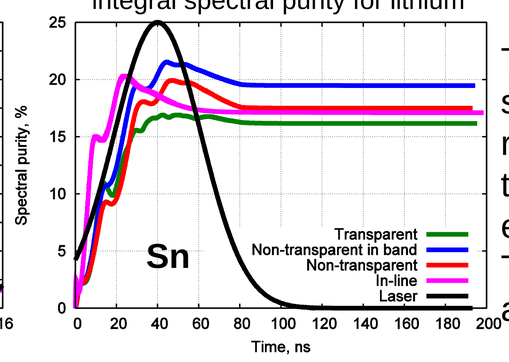


Figure 7. Time dependency of integral spectral purity for tin

The difference in ionization stage leads to difference in radiation spectra. In EUV band there are difference in radiation energy for considered cases. That is why spectral purity has a big difference (Figures 5,7).

Selfconsistent solution of the system of non-stationary detailed level kinetics in-line with radiative gasdynamics allows to get the correct ionization state of non-equilibrium plasma and more precise spectrum (see Figure 6).

SND_RUSAM in-line vs experiment

Laser: YAG 1.064 um;
pulse duration:10 ns; spot: 300 um
Lithium target: planar (experiment);
big sphere D=800 um (calculation).

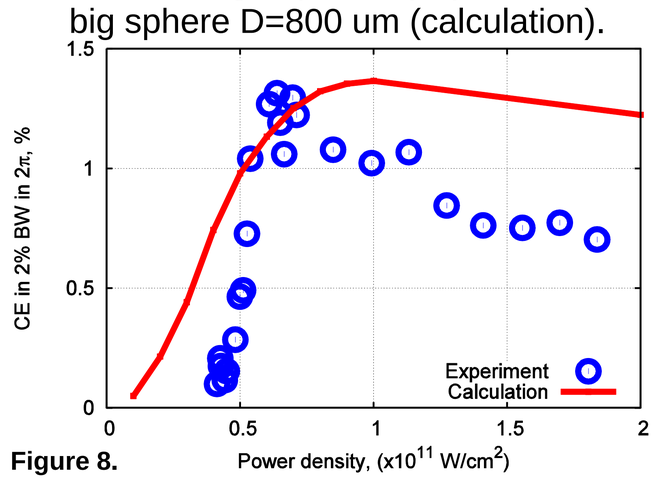


Figure 8.

Experimental data: *Takeshi Higashiguchi, Keita Kawasaki, Wataru Sasaki and Shoichi Kubodera,* Enhancement of extreme ultraviolet emission from a lithium plasma by use of dual laser pulses. Appl. Phys. Lett. 88, 161502 (2006); http://dx.doi.org/10.1063/1.2195904

Conclusions

- A model of non-stationary non-equilibrium radiating plasma is constructed
- Self-consistent solution of the equations of gasdynamics, detailed level kinetics and radiative transport equation is implemented
- Steady-state approximations and in-line method to account of level kinetics are considered and analyzed
- Effects associated with the non-equilibrium radiation field and the non-stationary solution of the system detailed level kinetics ("frozen ionization", spectra correction) are detected.

References

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